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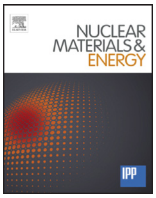

Structural evolution of tungsten surface exposed to sequential low-energy helium ion irradiation and transient heat loading

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ABSTRACT

Structural damage due to high flux particle irradiation can result in significant changes to the thermal strength of the plasma facing component surface (PFC) during off-normal events in a tokamak. Low-energy He^+ ion irradiation of tungsten (W), which is currently the leading candidate material for future PFCs, can result in the development of a fiber form nanostructure, known as “fuzz”. In the current study, mirror-finished W foils were exposed to 100 eV He^+ ion irradiation at a fluence of 2.6×10^{24} ions m^{-2} and a temperature of 1200 K. Then, samples were exposed to two different types of pulsed heat loading meant to replicate type-I edge-localized mode (ELM) heating at varying energy densities and base temperatures. Millisecond (ms) laser exposure done at 1200 K revealed a reduction in fuzz density with increasing energy density due to the conglomeration and local melting of W fibers. At higher energy densities ($\sim$ 1.5 MJ m^{-2}), RT exposures resulted in surface cracking, while 1200 K exposures resulted in surface roughening, demonstrating the role of base temperature on the crack formation in W. Electron beam heating presented similar trends in surface morphology evolution; a higher penetration depth led to reduced melt motion and plasticity. *In situ* mass loss measurements obtained via a quartz crystal microbalance (QCM) found an exponential increase in particle emission for RT exposures, while the prevalence of melting from 1200 K exposures yielded no observable trend.

1. Introduction

Advancement in fusion reactor design toward a successful power-producing device critically depends on details of plasma-material interactions under high particle and heat loads. Component failure during operation can seriously degrade plasma performance and material lifetime. Currently, tungsten (W) is considered the most promising candidate material for future plasma-facing components (PFCs) due to its high melting point, high thermal conductivity, and low sputtering yield [1].

However, studies done over the previous decade have shown that tungsten's capacity as a PFC material might be seriously compromised due to radiation damage from low-energy helium (He^+) ions. Researchers began to discover that within a certain temperature window, irradiation by high-flux, low-energy He^+ ions led to the growth of nanoscale, fiber-form tendrils [2–5]. He^+ ion-induced “fuzz” growth was then found during Alcator C-Mod testing, confirming that this structure could actually develop in a fusion device [6].

Since the discovery of fuzz formation, many different experiments have been conducted to try and characterize this heterogeneous surface structure. Work done in [7] found a reduction in the physical sputtering yield with fuzz growth. Other studies have shown a reduction in the unipolar arcing threshold on nanostructured W surfaces, which could lead to significant levels of erosion during device operation [8,9]. Research has also been performed to characterize the surface response during transient heat loading events. An edge-localized mode (ELM) is a destructive type of transient event that can occur during tokamak operation [10]. During an ELM, the edge plasma relaxes and imparts large heat fluxes onto the PFC surface. Type-I ELMs possess the highest flux and power loss when compared to other types of ELMs, making these events a critical point of concern for reliable operation [10]. This type of high cycle heat loading can lead to surface cracking, melting, and erosion of the material surface [10,11]. In addition, recent studies have discovered that fuzz formation could drastically decrease the thermal conductivity of the W surface, which would degrade tung-

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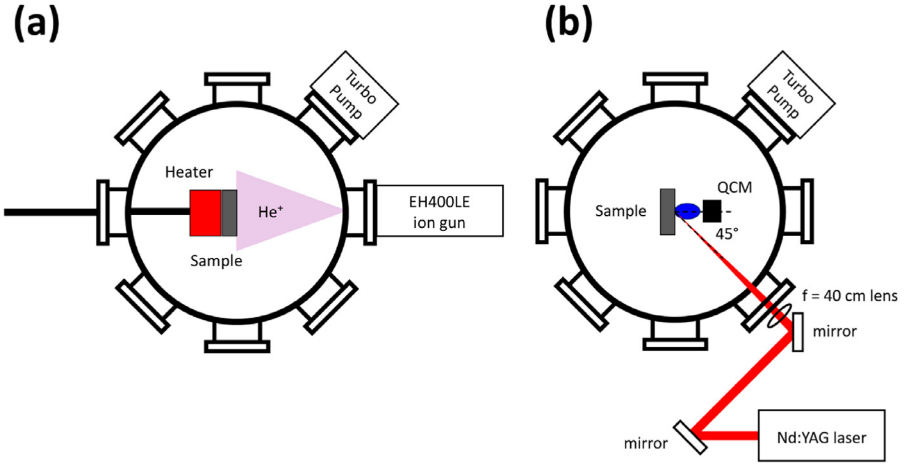

Fig. 1. UHFI-II chamber at CMUXE; (a) ion irradiation setup schematic & (b) long-pulsed laser irradiation setup schematic.

sten's thermal shock performance and exacerbate other material problems during transient heat loading [12,13].

Until recently, pulsed heat loading research has focused on low magnitude ELMs to determine damage and cracking thresholds. Higher magnitude ELMs have not been as widely studied because of techniques in development to "mitigate" ELMs to $\leq 0.5\,\mathrm{MJ\,m^{-2}}$ [13,14]. However, these mitigation techniques are not fully developed, so research on the melting and potential splashing of the $\mathrm{He^+}$ ion-induced fuzz nanostructure during unmitigated ELMs (energy densities up to several $\mathrm{MJ\,m^{-2}}$) remains important for the development of advanced PFCs [15,16].

The proposed study aims to investigate the structural and thermal response of nanostructured W to ELM-like heat loading using two different methods. Currently, pulsed heat loading experiments utilize long-pulsed lasers, electron beams, or plasma accelerators to replicate the flux and timescale of type-I ELMs [17]. After being exposed to low-energy $\mathrm{He^+}$ ion irradiation to initiate fuzz formation, tungsten samples were exposed to pulsed heat loading via either laser or electron beam irradiations at varying energy densities. Field-emission scanning electron microscopy (FE-SEM) was used to observe the degradation of nanoscale tendrils on the W surface during heat loading. In addition, an *in situ* quartz crystal microbalance (QCM) was used to measure particle emission from the sample surface. Instead of focusing on the absolute amount of material ejected from the surface, analysis focused on the relative trends in mass loss at different energy densities and surface conditions (*i.e.*, pristine *vs*. fuzz). Conducting a multi-faceted examination on the deformation and melting of nanostructured W due to various forms of pulsed heat loading is of great interest to understand the behavior of PFCs and to develop mitigation techniques during these transient events.

2. Experimental details

Research efforts were split between the JUDITH 1 (Juelich Divertor Test Facility in Hot Cells) facility [18] at Forschungszentrum Jülich and the UHFI-II (Ultra High Flux Irradiation - II) facility at the Center for Materials Under Extreme Environment (CMUXE) at Purdue University. Cold-rolled W samples (99.95% purity) with dimensions $10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 0.5\,\mathrm{mm}$ were cut from the same sheet and mechanically polished to a mirror finish devoid of major imperfections. First, samples were exposed to 100 eV $\mathrm{He^+}$ ion irradiation, with an ion flux of $7.2 \times 10^{20}\,\mathrm{ions\,m^{-2}\,s^{-1}}$ ($2.6 \times 10^{24}\,\mathrm{ions\,m^{-2}}$ fluence) at a temperature of 1200 K, using the UHFI-II facility illustrated in Fig. 1(a). The ion gun is a grid-less end-hall 'EH' ion/plasma source. The ion gun includes a broad beam End-Hall ion source and an automated power supply controller. The broad divergent beam improves throughput by uniformly covering a wide deposition zone.

After ion irradiation, some of the W samples were exposed to pulsed heat loading via long-pulsed laser irradiation. A schematic of the laser loading system is shown in Fig. 1(b). A 1064 nm pulsed Nd:YAG millisecond (ms) laser was focused onto the W fuzz surfaces, with a 1 mm spot size. The laser utilized a flat top beam mode to ensure even heating over the entire spot. W fuzz samples were mounted on a translational stage inside the chamber in order to attain multiple exposures, in an *in situ* condition, on one sample in a grid-like pattern. In order to replicate both the intensity and duration expected for type-I ELMs in fusion devices, the pulse width was set to 1 ms, the repetition rate was set to 1 Hz, and the energy density varied between the following values: 0.6 - $1.6\,\mathrm{MJ\,m^{-2}}$ ($19–57\,\mathrm{MJ\,m^{-2}\,s^{-1/2}}$) [19]. The heat load parameter (expressed in $\mathrm{MJ\,m^{-2}\,s^{-1/2}}$) is equal to the product of the power load ($\mathrm{MW\ m^{-2}}$) and the square root of the pulse duration ($\mathrm{s^{1/2}}$) [17]. Each exposure consisted of 200 pulses. In addition, W fuzz samples were set at different temperatures during exposures – RT and 1200 K – in order to determine the effect of the base temperature on the surface response.

During laser irradiation, a quartz crystal microbalance (QCM) was situated in front of the sample surface to detect any emitted particles. The QCM was oriented normal to the sample surface, with the crystal toward the laser-exposed spot at a distance of 20 mm. The resolution of the QCM is ±0.01 Å. The collection size of the detector surface is $52.18\,\mathrm{mm^2}$. During each exposure, the thickness of material deposited on the crystal is measured by an Inficon SQC-310 Thin Film Deposition Controller. The mass deposited was then calculated using the Sauerbrey equation [20]. Utilizing an *in situ* method to measure mass loss possesses inherent advantages over other *ex situ* techniques used in previous experiments. Significant amounts of oxide formation found in previous fuzz formation experiments on molybdenum after removing a sample from vacuum indicate that the added mass from oxides could confound *ex situ* mass loss measurements [21].

The remaining nanostructured tungsten samples were sent to Forschungszentrum Jülich and were exposed to pulsed electron beam irradiation in the JUDITH 1 facility. The schematic of the facility is shown in Fig. 2. The pulse width of the electron beam was set to 1 ms, and each exposure consisted of 200 pulses at an energy of 120 keV. By scanning a $4 \times 4\,\mathrm{mm^2}$ area at very high frequencies ($\sim 50\,\mathrm{kHz}$), the electron beam provided homogeneous heat loading during each exposure. To understand the surface response over a wide range of ELM intensities, exposures were done

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